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Transformation of Levantine Intermediate Water tracked by MedArgo floats in Western Mediterranean

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Abstract

A clustering methodology is applied to investigate the thermohaline structure of Levantine Intermediate Water (LIW) in the western Mediterranean basin. 16 free-drifting hydrographic profilers were deployed in the framework of the MFSTEP project (MedArgo component) from September 2003. A total of 925 CTD profiles data collected until the beginning of February 2006 have been used in the analysis. The results are in good agreement with the general circulation scheme for intermediate waters in the basin and confirm the hypothesis about a "discrete-continuous" thermohaline structure of LIW.

1 Introduction

Levantine Intermediate Water (LIW), the saltiest intermediate Mediterranean water mass, is formed in the northern part of the eastern basin. After sinking until its equilibrium depth, LIW is spread following the general circulation, and through the channel of Sicily enters into the western Mediterranean basin. Besides being relatively easily tracked in all Mediterranean sub-basins, some details of LIW thermohaline characteristics, modification processes, and circulation still require to be better understood (Millot, 2005). The most accepted LIW circulation scheme in the western Mediterranean was first proposed by Millot (1987): LIW entering through the Sicilian channel mainly contours cyclonically the successive western sub-basins as a geostrophic vein following the continental slope due to the Coriolis effect, although affected by the intense mesoscale activity typical of the Mediterranean Sea. A well-known sign of the presence of LIW in a CTD profile is the characteristic maximum of temperature (relative) and salinity (absolute) everywhere encountered in the range of depths going from 300 to 500 m. The erosion of these maxima is an indication of LIW transformation, by mixing with surrounding waters, along its westward path in the western Mediterranean, although sometimes less transformed waters are observed more to the west than the most transformed ones. This can be due to recirculation to the east of LIW that, after

OSD

3, 569–584, 2006

EGU

arriving to the entrance of the westernmost Alboran sub-basin, partly penetrates into it and contributes to the Mediterranean outflow through Gibraltar, and partly is entrained by the alongslope Algerian current flowing again to the Sardinia channel area, with the possibility of being spread seawards by meanders and mesoscale eddies generated in this unstable flow.

However, this may not be the only reason for the "anomalous" thermohaline spatial distribution of LIW in the western Mediterranean, in contrast with what should be predicted by models of a continuously transformed and isopycnically displaced layer. In 1985 the hypothesis of a "discrete-continuous" structure of LIW (Emelianov and Fedorov, 1985) was proposed. Based on the analysis of observational data and taking into account the "pulsating character" of LIW formation, which depends on both the climatic conditions throughout the year and the different areas of LIW formation in the eastern Mediterranean basin, it was proposed that the LIW layer can be thought as a "suspension". According to this idea, the suspension consists of background water with high temperature and salinity, in which lenses and sheets of even more saltier and warmer waters will be "suspended". The background layer is initially formed by LIW, sunk down to the corresponding isopycnal level in its formation region and being progressively incorporated to the circulation at intermediate depths. New volumes of LIW, generated due to surface layer density increasing by cooling in winter and their salinization due to evaporation in summer, continue to sink up to the depth of the isopycnal level of this background water (Ovchinnikov et al., 1976). These saltier and warmer volumes of LIW are eventually broken into smaller ones by mixing processes, mainly of double diffusion nature (Ruddick and Turner, 1979). The smallest lenses dissipate, maintaining the high temperature and salinity of the background layer. This picture becomes even more complicated in the western basin if we take into account that LIW displaces mainly in the form of veins, (Millot, 1999) which sometimes are affected by the large mesoscale eddies generated by the Algerian current. These eddies capture portions of LIW veins (Emelianov et al., 2000) and take them inside their circulation system (Millot and Taupier-Letage, 2005). The free-drifting hydrographic profiling floats launched in the western Mediterranean in the framework of the MFSTEP project (contribution to MedArgo, the Mediterranean component of the international Argo program), provided new data that allow monitoring the complex LIW thermohaline structure and its dynamics throughout the period of observation.

2 Materials and methods

CTD data from 16 floats operating in the western Mediterranean from September 2003 until the beginning of February 2006 (Table 1) were downloaded from the Coriolis data centre (http://www.coriolis.eu.org/cdc/projects/cdcMFSTEPFloats.asp). A total of 1018 profiling cycles produced 925 usable CTD profiles.

A first analysis of θ,S-curves of all the downloaded profiles was performed using Ocean Data View software (Schlitzer, 2004). This visualization showed that the LIW cores are situated in the range from 29.0 to 29.1 in sigma-θ, and that there is a wide range of thermohaline maxima ($13.1<\theta<14.35^{\circ}$C and $38.49<S<38.76$) associated with different shapes of θ,S-curves (Fig. 1). Objective cluster analysis (Kaufman and Rousseeuw, 1990) was used to classify the ensemble of LIW θ,S profiles to unveil classes of differently transformed waters. This type of analysis (also known as segmentation analysis or taxonomy analysis) seeks to identify homogeneous subgroups of cases in a given population. Cluster analysis allows identifying a set of groups which both minimize within-group variation and maximize between-group variation. Hierarchical clustering is based in three steps: first, definition of a distance between elements; second, selection of a linking method for forming clusters; third, determine how many clusters best suit to the data. A particular type of hierarchical clustering is K-means clustering, in which one specifies the number K of clusters in advance, and then calculates how to assign cases to the K clusters. We have applied a modified version of the K-means clustering methodology, in which instead of specifying the number of clusters we have specified the maximum cluster radius in the profile space. We will hence obtain the clusters by successively extracting the most representative or central profiles (that is, the ones which have the maximum number of other profiles at a distance smaller or equal to the maximum radius), up to exhausting the profile space or up having so small clusters that they are regarded as statistically non-significant. The value of the maximum radius has been selected by comparison of θ,S profiles obtained in different parts of the western Mediterranean (Emelianov et al., 2000).

We need first to define a reasonable notion of distance in the θ,S profile space. Given two values (θ_0,S_0) and (θ_1,S_1), in the θ,S plane, we define the distance between them as:

$$d\left((\theta_0, S_0), (\theta_1, S_1)\right) = \left[(\theta_0 - \theta_1)^2 + k^2 (S_0 - S_1)^2\right]^{1/2} \tag{1}$$

where the factor κ is the salinity-to-temperature aspect ratio and is expressed in °C/psu. We have conventionally fixed κ to 4°C/psu, what means that a separation of 1 psu can be considered equivalent to a separation in 4°C. We extend the point-to-point distance to a point-to-profile distance in the following way: given a point (θ_0,S_0) and a profile p={ (θ_i,S_i), i=1,...,N }, the distance d((θ_0,S_0),p) is given by

$$d\left((\theta_0, S_0), p\right) = \min_i d\left((\theta_0, S_0)\right), \left((\theta_i, S_i)\right) \tag{2}$$

Finally, the distance between two profiles p={ (θ_i,S_i), i=1,...,N } and q={ (θ_j,S_j), j=1,...,M } is defined as:

$$d(p, q) = \min\left(\sum_i d\left((\theta_i, S_i), q\right), \sum_j d\left((\theta_j, S_j), p\right)\right) \tag{3}$$

We proceed to classify profiles in two iterations for the θ,S profiles observed between 29.0 and 29.1 sigma-θ. In the first iteration, a maximum radius r=0.05°C was applied. This radius implies that, to be included in the same cluster, θ,S curves may differ at most in θ by 0.05°C or in S by 0.0125 from the central curve. In the second iteration, K-clustering was applied only to those θ,S-curves belonging to the largest cluster (Cluster 1) and the radius was reduced to the half, r=0.025°C. Thus, in this case θ,S curves with $\Delta\theta>0.025$°C and ΔS>0.00625 were separated in different clusters.

OSD

3, 569–584, 2006

EGU

3 Results and discussion

As a result of the first iteration seven clusters of θ,S curves were obtained (Fig. 2). The clusters are numbered according to the amount of profiles they include (the first cluster is the largest one and the seventh cluster is the smallest one). The representative θ,S curves of each one of the seven clusters are their "centres of mass" in the profile space.

In Fig. 2 one can see three main groups of clusters, represented by their centres of mass. Clusters representatives 2, 3 and 6 are situated in the saltier and warmer part of the θ,S plane, so corresponding to the saltiest LIW located in the Tyrrhenian sub-basin. Less saline cluster representatives 1, 4 and 5 include the profiles placed west of Corsica and Sardinia islands. Profiles included in cluster 7 lie in the Sardinia channel area, so establishing the transition between less and more transformed LIW. The profiles belonging to the largest cluster (number 1) are encountered everywhere west of Corsica and Sardinia, and they should be considered as the background LIW in terms of the Emelianov and Fedorov hypothesis. Less transformed LIW from cluster 4 (mostly near to the expected path of the northwards vein that contours the two islands after exiting the Tyrrhenian) and more eroded one from cluster 5 (in the westernmost part of the basin, where the main LIW vein is expected to have followed the continental slope until contouring the Balearic islands or crossed the channel between them and the mainland) are embedded into the area occupied by the background LIW from cluster 1. An interesting fact is that some floats sampled differently transformed LIW in consecutive casts. This means that the floats did not displace with the same portion of LIW and that their trajectories were mainly driven by surface drift, during their periodic ascent, surfacing and descent motions to transmit data by satellite link.

We illustrate this with a couple of examples (Figs. 3 and 4), where we grouped the set of profiles corresponding to a single part in differentiated blocks on the θ,S diagram (not corresponding to the clusters). The clearest example is the float 6900294, which crossed the Sardinia channel moving eastwards, and sampled first transformed LIW (cluster 4), then intermediate stages (clusters 7, 3 and 6), and finally the less

OSD
3, 569–584, 2006

transformed LIW (cluster 2), situated in the Tyrrhenian (Fig. 3). Taking into account the LIW circulation scheme from (Millot, 1999) the float was conducted to the Sicily channel by the Algerian current (B), probably after being trapped by a large mesoscale eddy around 38° N (A), and then re-entered the Tyrrhenian sub-basin maybe due to the bifurcation of the surface current system that takes place in this area (Font at al., 1998), until sampling the less transformed LIW in a single profile (D) north of Sicily, where LIW recently entered from the eastern Mediterranean is expected to be found. During this change the float sampled the saltiest LIW situated in the narrowest part of the Sicily channel between capes Lilibeo and Bon, just after the western sill (C). The θ,S curve from this cast is relatively uniform and does not have the thermohaline inversions often observed in the θ,S profiles in other areas of the basin. This demonstrates the important role of Mediterranean straits in modification of water thermohaline structure (Astraldi et al., 1999) and confirms the hypothesis about "focusing effect" of the straits (Emelianov and Fedorov, 1985), what means that in the narrowest parts of the channels and above the sills, the mixing processes are more intense, what leads to homogenization of LIW and to destruction of warmer and saltier lenses. After crossing the channel area, as current velocities diminish, LIW thermohaline inhomogeneities begin to appear, because of the remaining excesses of salt and heat.

Another example of changes in the LIW θ,S structure is presented in Fig. 4. In this case, float 6900278 derived southward along the Spanish continental slope, sampling at the beginning the less transformed LIW situated between 42° and 40°30′ N. Between 40°30′ and 39°30′ N, more transformed LIW was encountered. At the end of that trajectory, first moving close to the Spanish coast and then close to the Algerian coast, the float sampled LIW with lower salinity, most likely due to coastal water influence. Except in the final part of its trajectory, this float displays a "classical" behaviour, following the general alongslope cyclonic circulation while progressively eroding its LIW signature.

The second iteration of K-clustering was applied just on θ,S-curves of the largest cluster 1 with the search radius reduced to a half (r=0.025), in order to reveal subtler differences in the profiles included in this class. As the result of the second iteration, Cluster 1 was split into five sub-clusters (Fig. 5). As shown in the figure, the spatial distribution of sub-clusters is characterized by its patchiness. Consecutive θ,S profiles sampled by the same float show that less transformed LIWs very often incorporates more transformed ones. This situation can be explained from the point of view of the "discrete-continuous" structure of this water. During its displacement, the float samples different parts of a continuously-transforming background layer, so encountering different volumes of LIW with different values of temperature and salinity.

It is necessary to note that our analysis does not consider the time component; we just analyzed the spatial θ,S variability of LIW. Probably, taking into account time variability it will be possible to provide a better track on the spatial distribution of differently transformed profiles and hence to reduce the degree of patchiness observed in the sub-classification of background layer waters, represented by the largest cluster.

4 Conclusions

The clustering method used to analyze the θ,S profiles in the western Mediterranean allowed classifying in a canonical, automatic way the spatial distribution of differently transformed LIW. According to the interpretation of LIW proposed by Emelianov and Fedorov (1985), the characteristic θ,S profile associated to background LIW defines the largest class of similar (i.e., close) profiles, with the largest range of temperature and salinity differences. We have also shown that differently transformed intermediate waters were embedded into this background but at specific, different geographical areas of the Mediterranean western basin.

When the class defining the background is studied in further detail by reducing the allowed cluster radius, we observe that the new classes of profiles present a characteristic patchiness in spatial distribution of differently transformed LIW.

The obtained results are in good agreement, so can be considered as a confirmation, with the hypothesis about "discrete-continuous" thermohaline structure of Levantine Intermediate Water. They also confirm the general LIW alongslope cyclonic circulation pattern proposed by Millot for the western Mediterranean, with disturbing effects that can be due to interaction with mesoscale eddies in the southern part of the basin.

Another conclusion, evidenced in the case shown in Fig. 3, is that the MedArgo profiling cycle (reduced to 5 days to optimize the requirements for data assimilation in the MFSTEP operational model) can have as a consequence that the trajectories of the floats may not be representative of the circulation in their parking depth (350 m), The drag their suffer while are ascending through upper water layers, remaining at surface while emitting the profiles information, and descending again to the parking depth (total of 8–12 h) can have a stronger influence on the horizontal float motion than the time they remain at 350 m (or deeper to profile from 750 or 2000 m, depending on the cycle), then altering the Lagrangean information we can retrieve from them on LIW circulation.

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Table 1. MEDARGO floats status (8 February 2006).

No.	Model	WMO code	Deploy date	Lat	Lon	Cycle	Last date	Lat	Lon	Status*
1	APEX	6900226	26 Sep 2003, 15:25	41.75	3.72	12	7 Nov 2003, 15:30	41.16	3.62	R
2	APEX	6900227	26 Sep 2003, 15:06	41.73	3.72	6	11 Nov 2003, 07:24	41.32	2.26	R
3	PROVOR	6900228	2 Oct 2003, 17:27	41.60	3.77	10	7 Nov 2003, 15:30	41.17	3.81	R
4	PROVOR	6900229	2 Oct 2003, 18:33	41.60	3.73	5	7 Nov 2003, 15:32	41.28	3.92	R
5	APEX	6900278	30 June 2004, 13:43	41.61	3.94	77	30 June 2005, 14:01	37.40	−1.40	D
6	APEX	6900279	30 June 2004, 12:18	41.75	3.82	105	8 Oct 2005, 11:11	39.47	3.29	D
7	APEX	6900280	16 Aug 2004, 10:00	38.85	12.97	108	7 Feb 2006, 11:12	41.75	11.29	A
8	APEX	6900281	15 Aug 2004, 20:08	39.61	12.42	107	6 Feb 2006, 21:20	41.35	11.36	A
9	APEX	6900282	15 Aug 2004, 10:46	40.17	11.98	106	6 Feb 2006, 09:57	38.89	9.36	A
10	PROVOR	6900291	7 Sep 2004, 02:14	41.68	6.10	82	19 Oct 2005, 06:41	42.10	8.12	D
11	PROVOR	6900292	7 Sep 2004, 08:32	40.67	6.10	104	7 Feb 2006, 07:44	40.92	4.75	A
12	PROVOR	6900293	7 Sep 2004, 15:23	39.65	7.12	104	6 Feb 2006, 06:28	42.30	7.00	A
13	PROVOR	6900294	8 Sep 2004, 04:27	38.63	7.12	72	5 Sep 2005, 07:24	38.42	13.36	D
14	PROVOR	6900295	26 Oct 2004, 09:15	37.86	0.68	30	22 March 2005, 08:22	37.58	5.30	D
15	APEX	6900300	27 Sep 2005, 10:45	41.17	2.61	26	4 Feb 2006, 12:50	38.45	0.30	A
16	PROVOR	4900556	22 March 2005, 23:54	41.59	4.61	64	8 Feb 2006, 01:21	36.14	−1.19	A
	TOTAL					1018				

*R-Recovered, D-Dead, A-Alive, S-Surface

OSD

3, 569–584, 2006

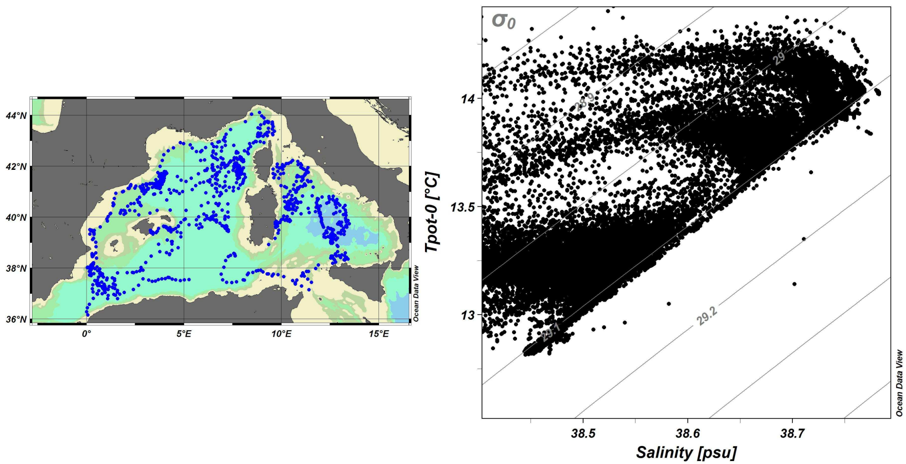

Fig. 1. Floats position and corresponding θ, S-curves during all period of observation. Light colour marks the continental shelf and slope area (until 500 m).

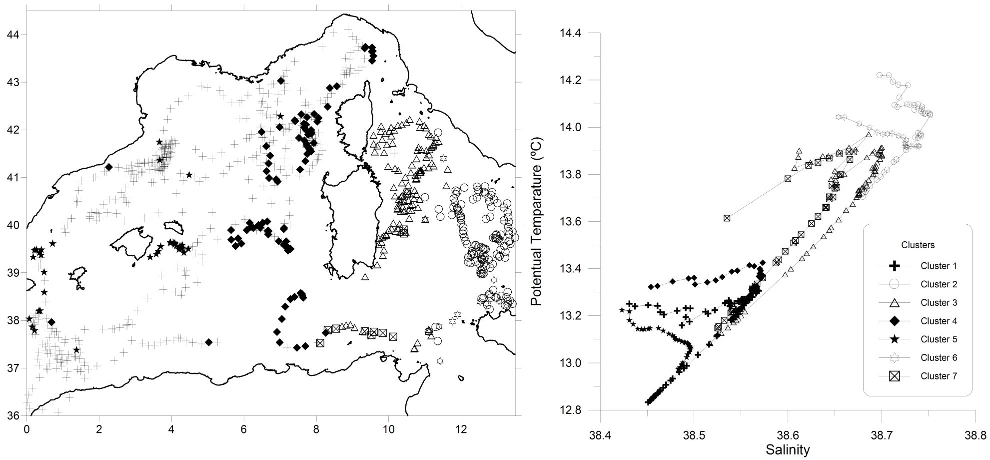

Fig. 2. Left: Float positions, labelled according to the cluster they belong to. Right: Representative θ,S curves obtained during the first iteration.

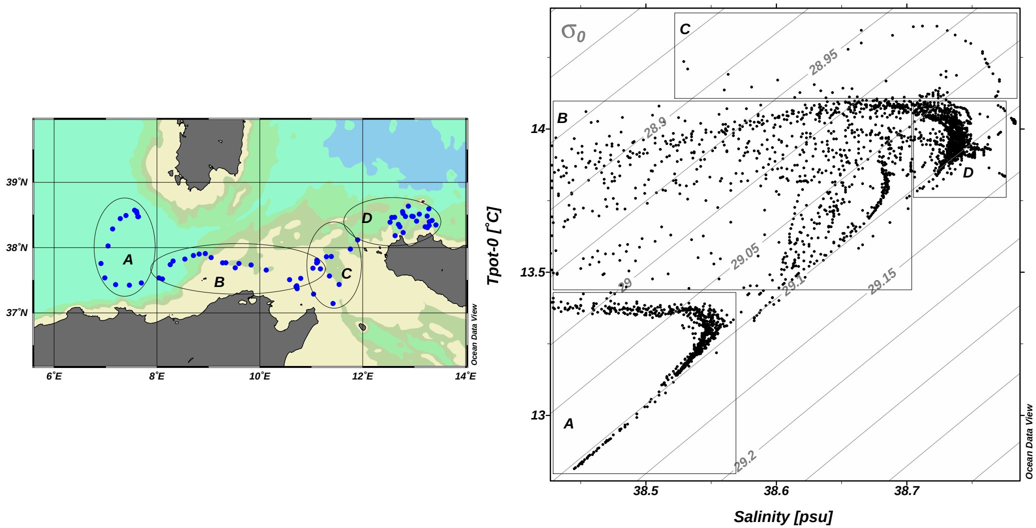

Fig. 3. Float PROVOR 6900294 trajectory and θ,S curve.

OSD

3, 569–584, 2006

EGU

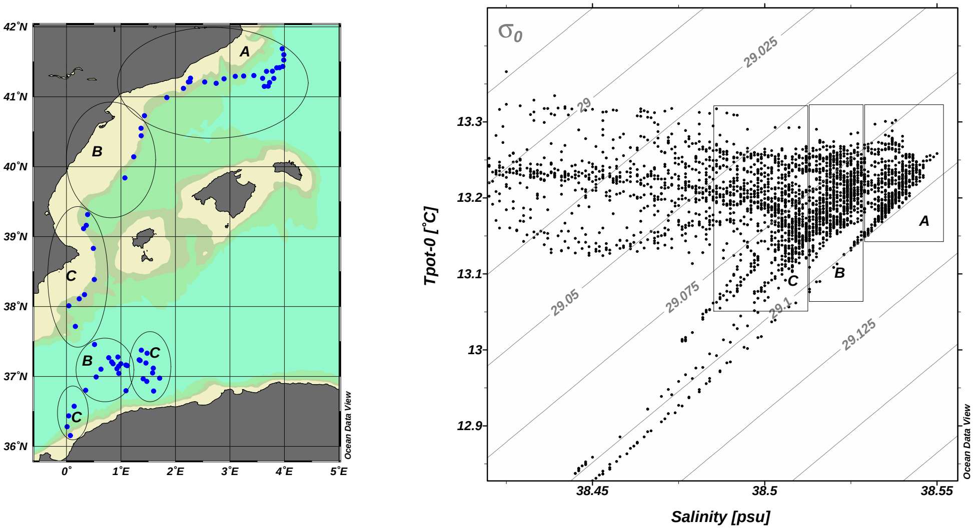

Fig. 4. Float APEX 6900278 trajectory and θ,S curve.

OSD

3, 569–584, 2006

Transformation of Levantine Intermediate Water

M. Emelianov et al.

EGU

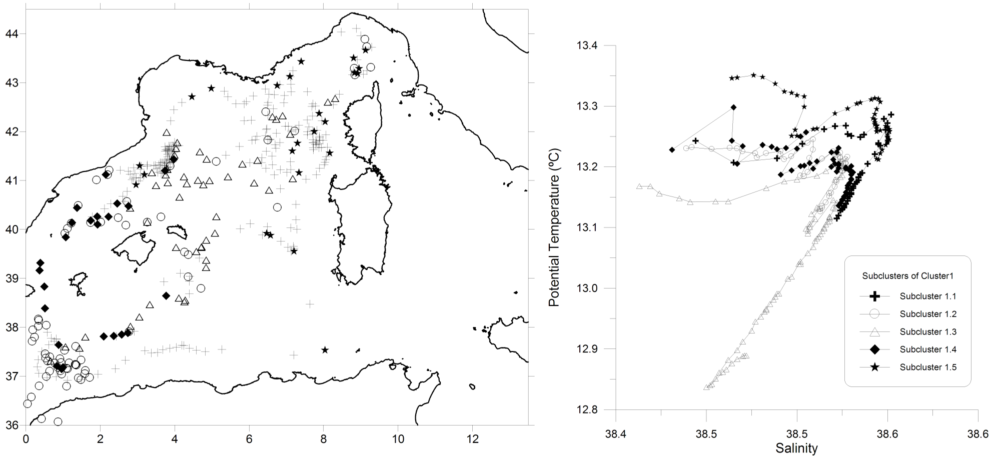

Fig. 5. Left: Float positions of Cluster 1 floats, labelled according to the sub-cluster they belong to.
Right: Representative θ,S curves obtained during the second iteration.